ERDC TN-DOER-T12
May 2016

Evaluation of Channel Infill Processes in Relation to Forcing Data

by Lauren Coe and Ashley Frey

PURPOSE: This U.S. Army Corps of Engineers (USACE), Engineer Research and Development Center (ERDC), Dredging Operations and Environmental Research (DOER) Program technical note (TN) explains processes that contribute to infilling of channels and basins in coastal regions where salt water and fresh water mix. It briefly discusses methods to reduce this infilling. Future activities of this DOER research task will identify connections between infilling mechanisms and forcing data. This will aid in developing a general method to use these types of data collectively as a tool to estimate future dredging volumes as well as likely location and sediment composition of these dredging events.

BACKGROUND: Shoaling is a principal maintenance concern for nearly all maintained waterways. Sediment management methods to reduce dredging needs, and innovations to streamline the dredging process, are important tools for those tasked with keeping channels and harbors navigable. However, the general processes that influence channel shoaling, and the site-specific conditions, are also valuable when attempting to predict what type of sediment will need to be removed in the next dredge cycle as well as where in the channel the sediment is likely to accumulate. This knowledge is helpful in planning beneficial use projects and, when paired with historical dredge history data, can improve estimation of expected future dredging needs. Channel processes driven by forcing data such as rainfall, the tidal cycle, and river discharge are important for determining shoaling patterns on a site-specific basis. This note will explain how these forcing data generally influence infill processes. Naval Station Mayport, FL, will be used to illustrate some of these mechanisms and their impact on sedimentation in different regions. As a reference, Figure 1 shows greater Jacksonville, FL, area, and Figure 2 shows the planview area of interest located at the mouth of the St. Johns River (SJR).

UPSTREAM SHOALING MECHANISMS: River discharge is directly related to sediment load and is often the source of cohesive sediments that are transported downstream to navigation channels, harbors, and inlets or estuaries near river’s mouth. Sediment transport in rivers is dictated by its continuous push towards dynamic equilibrium. A river that is sediment starved (by a dam, for example) may begin to erode the sides and bottom and carry sediment until equilibrium has been surpassed and deposition occurs further downstream. Diversions from the main stem of a river put in place for coastal restoration or flood control reduces the river flow and can exacerbate downstream shoaling if sediment supply remains greater than the reduced transport potential (Brown et al. 2013).

Figure 1. Jacksonville, FL, area and coastline.

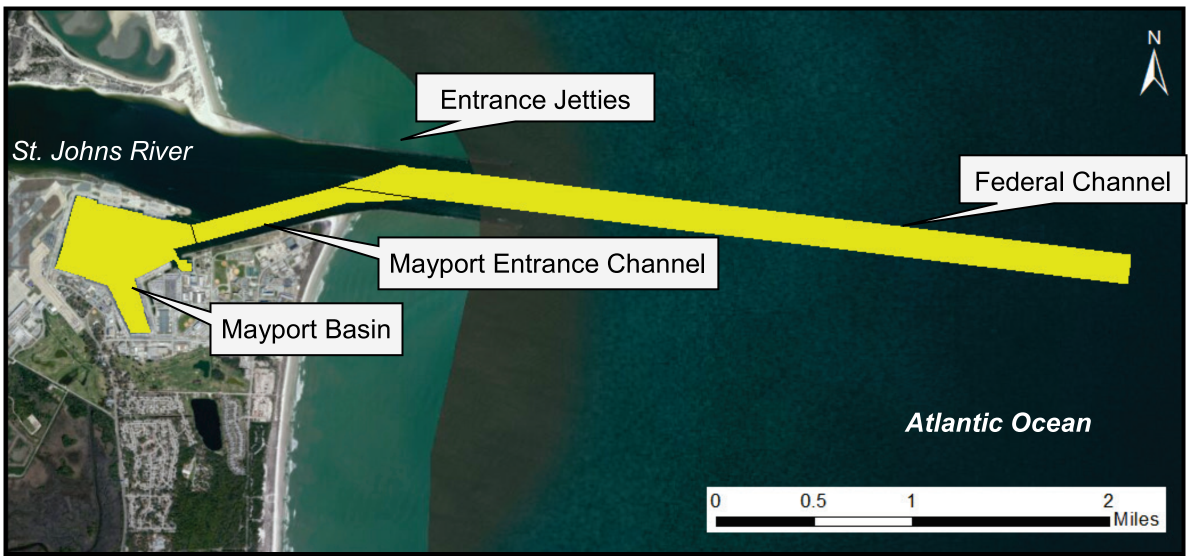


Figure 2. Mayport turning basin and entrance channel locations.

Precipitation provides the water that drives flow in surface waters through surface runoff and groundwater recharge for spring-fed channels and influences sediment transport both in runoff entering the channel and increasing river discharge quantities during major precipitation events. At the other extreme, droughts will decrease the streamflow of a river, thus decreasing its sediment transport potential to downstream areas. During prolonged droughts, soil is often more exposed either due to decreased land cover or the receding water levels and therefore more prone to erosion by wind or rain. Additionally, a major storm or rain event after a drought period can bring greater than usual amounts of sediment to a channel due to the increased erodibility of the drought-induced exposed land surface.

To illustrate this relationship, annual peak stream flow for the St. Johns River U.S. Geological Survey (USGS) Jacksonville station and Jacksonville rainfall were plotted (USGS 2015. Figure 3 shows the rainfall and peak streamflow from 1998 to 2013. The two sets of data show similar peaks corresponding to hurricanes Georges (Sep 1998), Charley (Aug 2004), and Fay (Aug 2008), and dips surrounding three periods of drought in Florida 1999 to 2002, 2006 to 2007, and 2010 to 2011.

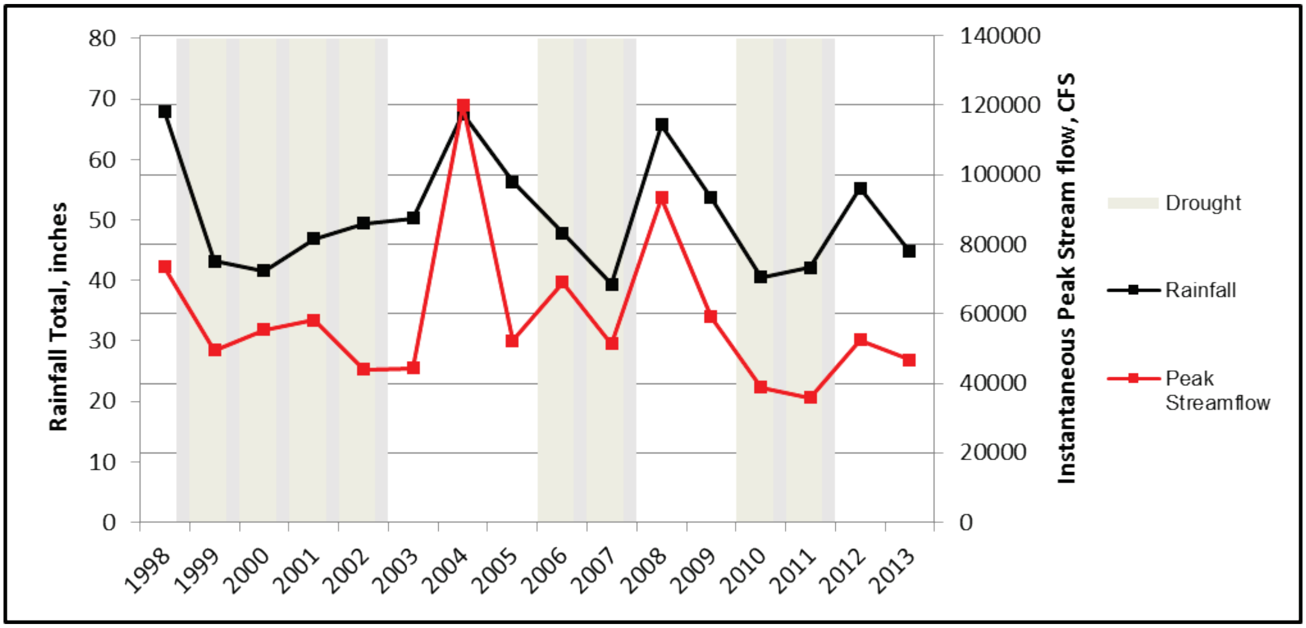


Figure 3. Rainfall at Jacksonville and peak streamflow of St. Johns River (1998–2013).

The Navigation Shoaling Analysis Tool (NSAT) was developed in 2012 at the ERDC Coastal and Hydraulics Laboratory (CHL) as part as of a study to predict dredging requirements for budget planning purposes at various U.S. Navy sites including NAS Mayport (Thomas and Dunkin 2012). The tool was developed to estimate shoaling between hydrographic surveys based on computed volume gain or loss on the digital elevation model (DEM) surface. The results of this tool for the Mayport Basin and entrance channel were averaged over the entire period and then separately over periods of drought and periods immediately following peaks in rain and peak streamflow. These results are presented in Table 1. Drought periods have slightly lower shoaling estimates when compared to all years, and periods containing the large peaks in rainfall and streamflow have the highest estimated shoaling based on the tool results.

Table 1. Estimated shoaling for Mayport basin and entrance channel.

Period Classification	Est. Annual Shoaling, cy
Full Period (1998–2010)	159,000
Drought Periods Only	135,500
Peak Periods Only	308,500

The SJR passes through the Federal entrance channel and empties into the Atlantic Ocean. High silt and clay concentrations found in the turning basin are contributed from river flow as it makes its way to the mouth. In the case of Mayport, approximately 800,000 cubic yards (cy) are dredged approximately every 2 years. Despite the relationship between rainfall and river discharge and sediment transport potential, there is not an identified direct correlation between an increase of rainfall in the preceding hydrologic year (October through September) and increased dredge volumes during the following dredging events. Rainfall and storm activity are not the sole factors influencing shoaling. Rates of shoaling do not necessarily correspond to the volumes dredged because budget and other constraints dictate the extent of dredging activity.

TIDAL MECHANISMS: Tides have an impact on sedimentation in navigable waters situated on tidal rivers or estuaries. Two characteristics of estuarine hydrodynamics drive transport processes in the majority of estuaries. The first of these is the oscillatory nature of tidal flow and vertical circulations introduced by density gradients between fresh and saltwater. The second aspect is the period of slack between phases of the tidal cycle (Ariathurai et al. 1983).

Salinity-driven density currents induce a vertical structure of dense saltwater flowing upstream near the bottom of the water column and less dense freshwater flowing downstream or seaward along the surface. Although flow reverses from ebb to flood periods, there still exists a net upstream or downstream flow in the respective column depths. This is referred to as flow predominance and can be quantified with the percentage of the flow at a given point that travels in either direction. At a point between locations with opposing predominance, there exists a null point with no dominant flow direction where the current directions are at mass balance over a cycle. This point is often found near the limit of salt intrusion where salinities are between 1 to 5 practical salinity units (PSU) (Schoellhamer 2000). Increased sediment concentrations often occur at these points of turbidity maxima, and heavy shoaling areas are often found nearby. This null point and associated high shoaling areas can be shifted, typically in the upstream direction, through deepening or the extension of the channel (Bruun 1994). The point may also shift throughout the tidal cycle, moving downstream during ebb periods and farther upstream during the flood (Eisma 1998).

Ideally tidal currents have equal ebb and flood duration with equal magnitude of currents, but in reality estuaries and tidal rivers often exhibit a tidal asymmetry. Tidal asymmetry will lead to a net seaward transport (ebb asymmetry) or net landward transport (flood asymmetry). If the duration of the falling tide exceeds that of the rising tide leading to a larger peak flood current, the system is referred to as flood dominant. If the duration of the falling tide is shorter than that of the rising tide leading to a stronger peak ebb current, the system is referred to as ebb dominant. Velocity asymmetry can also be induced by higher harmonics of the tidal constituents. This is referred to as an overtide and occurs when second harmonic frequency is an exact multiple of the principal component frequency. Phase lags between the two constituents can induce flood or ebb dominance, with a lag of π to 2π indicating flood and 0 to π indicating ebb dominance (Walton 2002). Estuaries with extensive tidal flats and little change in channel cross-section geometry are typically ebb dominant. Estuaries with fewer tidal flats and more time-variable channel cross-section geometry are likely flood dominant (Speer 1984).

Table 2 presents these distinctions between flood and ebb asymmetric tidal rivers or estuaries.

Table 2. General characteristics of flood and ebb tidal asymmetry.

Flood Asymmetry	Ebb Asymmetry
Longer falling than rising tide	Longer rising than falling tide
Higher peak flood current velocity	Higher peak ebb current velocity
Phase difference of principal and secondary harmonic between π and 2π	Phase difference of principal and secondary harmonic between 0 and π
Few tidal flats	Extensive tidal flats

Figure 4 and Figure 5 demonstrate the slight ebb dominance at Mayport. There is a higher peak ebb current velocity (> 2 knots, Figure 4A) compared to peak flood currents (1.8 – 2 knots, Figure 4B). National Oceanic and Atmospheric Administration (NOAA) tide tables for Mayport indicate a slightly longer rising tide than falling tide by approximately 1 hour (hr) (NOAA 2014). Figure 5A shows that the minimum salinity (PSUs) near Mayport occurs approximately 1 hr before ebb slack period, and the maximum salinity (Figure 5B) occurs approximately 1 hr before the flood slack period. Salinity has been shown to increase aggregation of cohesive sediments in suspension (Maggi 2005) and in turn, can enhance the settling of the flocs. The fact that high salinity occurs shortly before a low-energy slack period lends to deposition upon this slack period. Note that the times for events in the tidal cycle are approximate and based off the NOAA St. Johns River Operational Forecast System (SJOFS) to show only the general progression of tides near Mayport.

WIND-DRIVEN MECHANISMS: Winds are another important meteorological forcing factor that influences flows in navigation channels both when considered in the context of strong tropical storms as well as the typical wind direction at a site. Winds impact lateral and axial salinity contours within a channel as well as cross-channel sediment processes. Chen et al. (2009) determined that wind can induce lateral (cross-channel) circulations that influence sediment transport. A model was used to determine lateral sediment fluxes, salinity over the cross section, and lateral shear stress induced by down-estuary wind (in the direction of river flow) and up-estuary wind (against the direction of river flow) throughout the tidal cycle. The study found that salinity was consistently higher on the shoals, creating a density gradient that drives flow to the channel center. Conversely, during down-estuary winds, higher salinity in the channel circulates flow towards the shoals. During down-estuary winds it is expected that sediment is transported from channel to shoal, and up-estuary winds transport sediment from shoal to channel. Additionally, the wind direction can either increase stratification in a channel (down-channel winds) or decrease stratification (up-channel winds) (Scully et al. 2005).

Knowledge of the prevailing wind patterns at a site will aid in the prediction of shoaling locations within a channel cross section. This knowledge can also be implemented to determine the effects in the channel of a storm based on strength and direction of winds. At Mayport, winds prevail from the northeast or southwest depending on the time of year. The dominant wind direction aligns with the flow direction and can increase or decrease salinity levels upstream as it compounds with or reduces tidal driven salinity inflow (Giardino 2009).

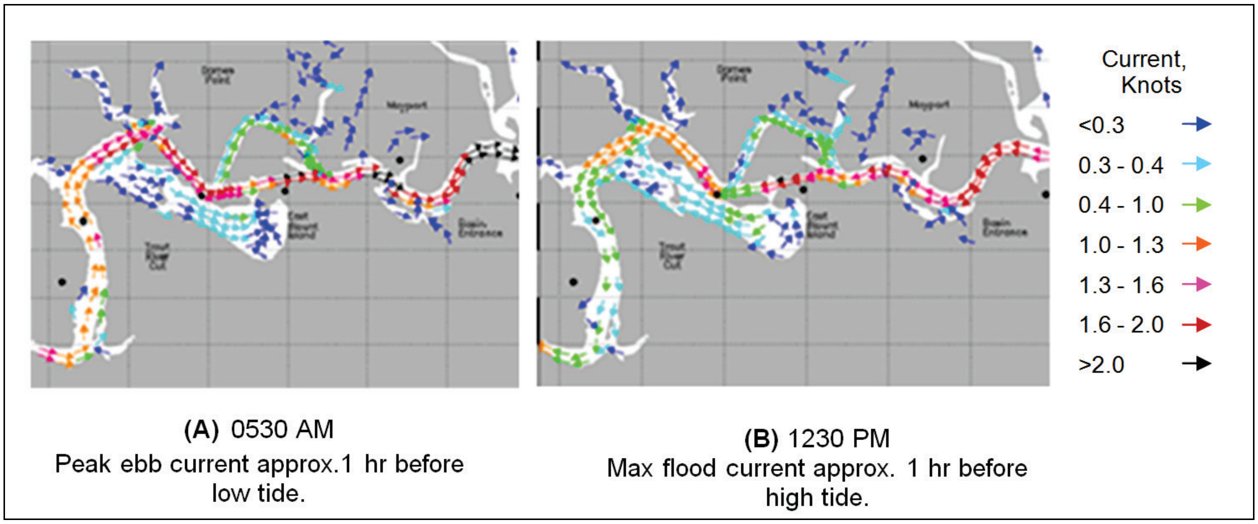


Figure 4. Current velocities of peak ebb (A) and peak flood (B). (NOAA 2014)

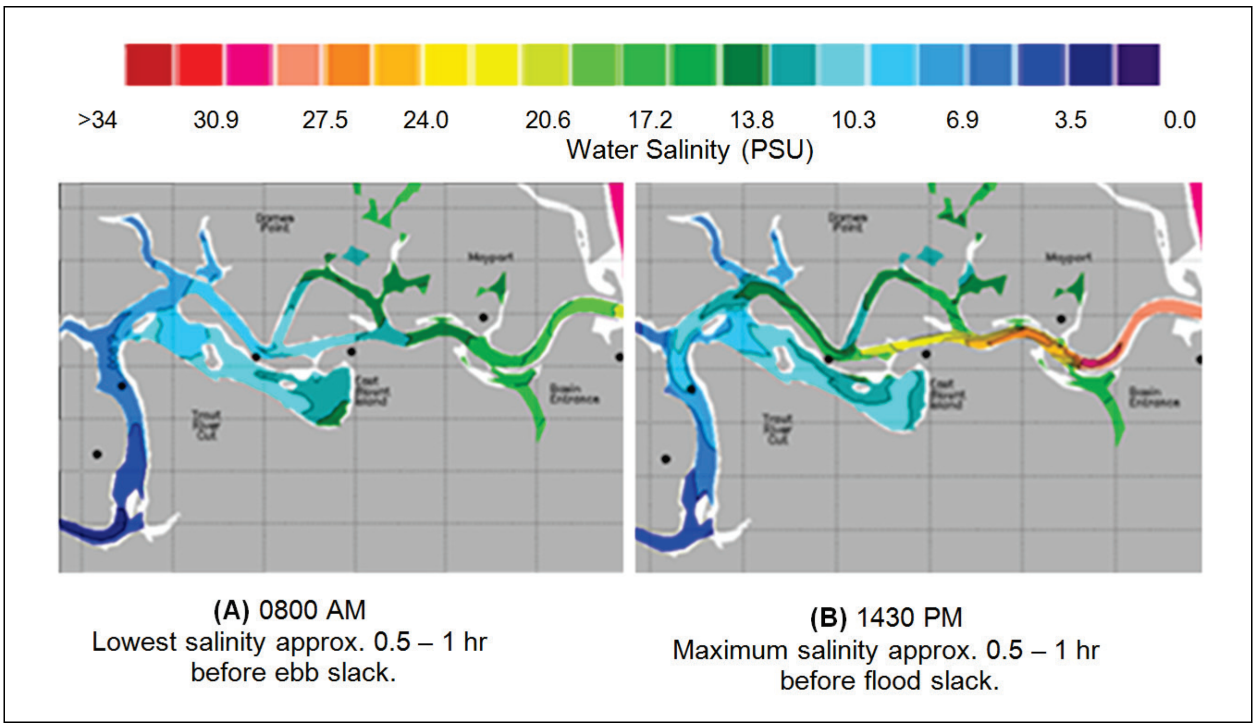


Figure 5. Salinity extremes prior to ebb slack period (A) and flood slack period (B). (NOAA 2014)

WAVE AND COASTAL MECHANISMS: Waves are generated as wind blows over fetches on the open ocean or by nearshore winds. As waves approach the beach, they begin to conform to the shape of the shoreline and reach the shore at an angle. Their energy generates longshore currents that carry sediment along the beach as it is stirred by breaking waves. The net direction of a longshore current is typically known, and jetties are constructed in consideration of the flow patterns of sediments in the littoral zone to keep coastal inlets clear for navigation. Although the jetties keep most sediment out, there is a fraction that goes through or around the structure.

Entrance channels at coastal inlets can experience bank encroachment on the updrift side of longshore transport causing asymmetric channel profiles. Areas downstrream of a jetty often suffer extreme erosion due to the trapping of sediment on the updrift jetty, starving the system of sediment. This area is a common site for dredged material placement to renourish the beach. This beneficial use of sediment may actually induce more shoaling because wave refraction on the ebb tidal delta and flood tides can cause a local reversal of the net longshore transport which pushes sediment back into the channel (Rosati and Kraus 2000). Along the Atlantic coast just north of the mouth of the SJR, the net longshore transport direction is north-to-south, and there is a local reversal south of the downdrift jetty (Figure 6).Winds and waves associated with tropical storms induce a local short-term reversal of longshore transport that may cause the channel to shoal in atypical ways.

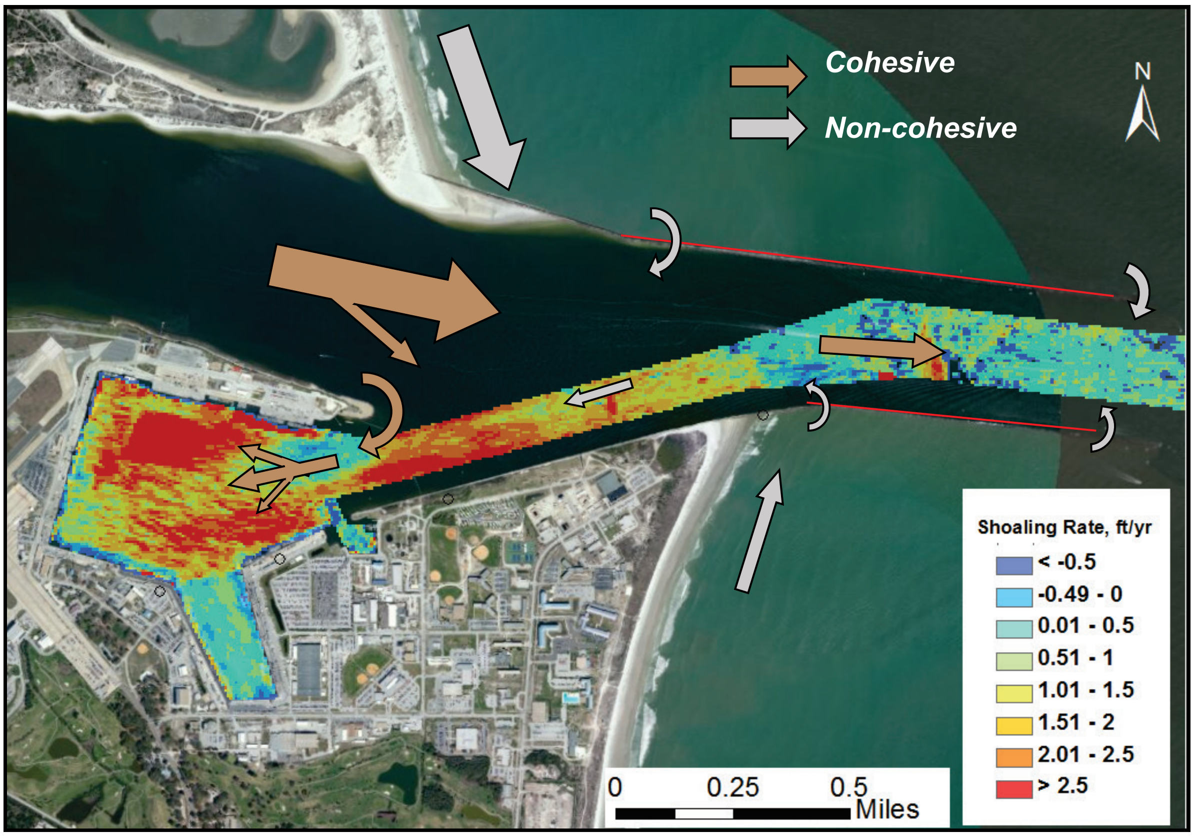
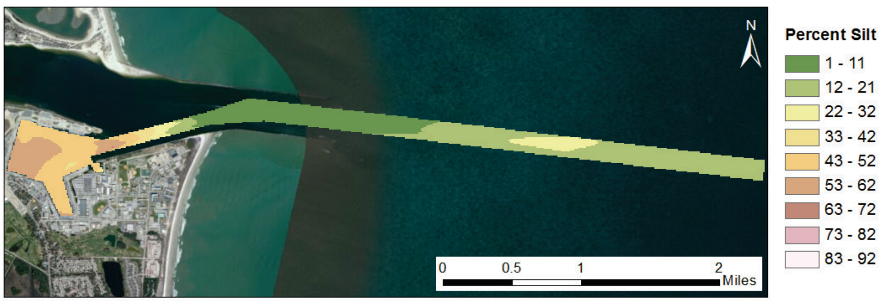


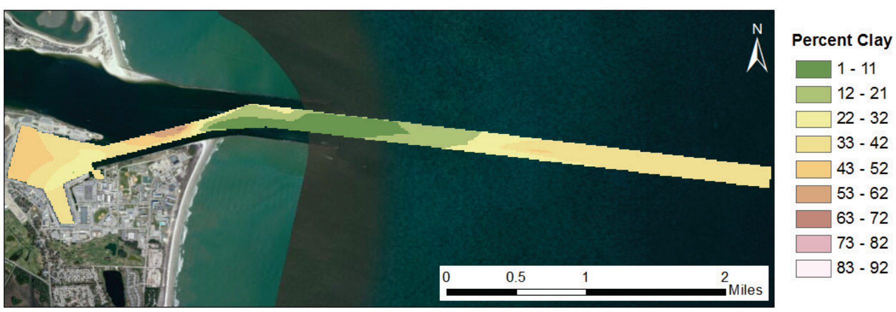
Figure 6. Sediment transport pathways for cohesive (brown) and noncohesive sediments (tan) in Mayport Basin and near SJR jetties (red lines).

SUMMARY OF MAYPORT PATHWAYS: The processes that influence shoaling in channels and harbors discussed in this technical note provide a basis for understanding transport pathways common at a site. Those pathways likely at work at Mayport will be summarized.

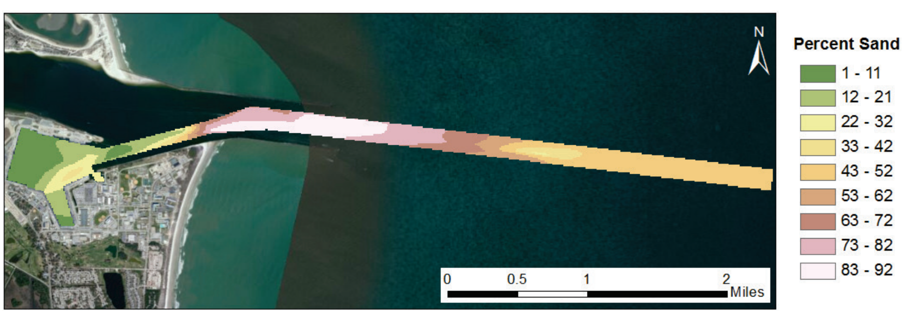
The Mayport basin and entrance channel exhibit shoaling rates of up to 2 feet (ft)/yr in some areas. Steady sedimentation is concentrated in certain areas due to the system geometry that lends to sediment settling in lower energy areas. In the entrance channel, there is evidence of clay being contributed on the northern part of the channel where it meets the SJR (Figure 7B). River flow encounters the wider geometry at this junction of the channel and the SJR and slows down, thereby allowing for the settling of suspended fines. This implies that an increase in river discharge would increase clay content and overall deposition in the entrance channel. Figure 6 shows the average rates of shoaling in the entrance channels and Mayport basin and superimposed sediment transport paths to better illustrate where sediment comes from and eventually ends up at this site. Cohesive sediments travel from upstream in the SJR, and a portion is transported into the basin or channel while the rest is flushed out during ebb tide. Longshore sediment transport brings sand predominantly from north to south. Some of this material is trapped north of the north jetty, and the remaining portion passes through or around the jetties. A small portion of this coarse material is transported farther up the channel which constitutes the small sand percentage in the turning basin. Some sand may also be present in riverine flow (Thomas and Dunkin 2012).



(A)



(B)



(C)

Figure 7. The percent of silt, clay, and sand in Mayport Basin and entrance channels based on sampling. (NAVFAC 2008)

INFILL PROCESSES AND SEDIMENT CLASSIFICATION: Cohesive sediment (clays and silts) transport is driven by aggregation of individual particles and shear stresses that dictate the critical value for both deposition and suspension in the water column. The aggregation of these small particles into flocs allows for settling at significantly higher velocities as compared to individual particles.

Noncohesive sediments (sands, gravels, and some silts) are transported as individual grains, and there is often a continuous exchange of grains on the bed and in transport. This process gives way to undulating bed forms in the transport of coarse sediments as particles are carried short distances by the flow before settling.

Typically, the percent of sand increases in the entrance channel in the seaward direction, and clays and silts are more predominant in the upstream direction. The sand fraction is greatest in the littoral zone where sand is moved in the longshore direction and escapes over and slips around the jetties at the entrance (Thomas and Dunkin 2012). Outside the zone of sand transport in the channel, the clay percentage increases due to the presence of marine clays. Figure 7 shows the percentages of silt, clay, and sand (respectively) in the Mayport basin and entrance channel.

Fines are brought to the mouth of the SJR from upstream in a relatively disaggregated condition typical for freshwater sediments and brought into the Mayport basin during ebb tide where freshwater laden with silts and clays flows seaward. As velocities begin to drop off during periods of low energy, these fines begin to flocculate and settle into the lower water column where incoming saltwater that flows along the bottom carries the sediment farther into the basin during flood tide. The basin is low energy compared with the narrower entrance channel, and sedimentation of this fine material occurs there (Figure 7A and Figure 7B).

DEEPENING AND NEW WORK IMPACTS: The deepening of navigation channels and harbors, also known as new work dredging, has become more common as vessels become larger and need deeper waters for safe navigation. This new work dredging that increases channel dimensions can lead to changes in dredging volume requirements and dredging requirements in new locations. As stated previously, deepening or lengthening of a channel can shift the null point and its associated areas of high deposition up the channel or river. Additionally, deepening can make dredging necessary in areas that previously required no maintenance dredging if deposition increases above a certain threshold that prohibits safe navigation.

At Mayport, a deepening project in the Mayport entrance channel, basin, and Federal entrance channel was completed in August 2012. Dredging data for events since that project have not been collected, but a 2008 environmental impact study by the U.S. Naval Facilities Engineering (NAVFAC) (2008) estimated the change in dredging requirements after the deepening project. Table 3 presents the estimated changes in deposition rates at Mayport. The only area estimated to see a decrease in shoaling rates is the dredged portion of the turning basin (Figure 2); however, this is due to sediment being pushed farther to the western end of the basin, which sees a 12% increase in deposition rates. While this portion of the basin was previously undredged, it may or may not remain so, illustrating how deepening projects have the potential to bring about dredging requirements in new areas.

Table 3. Estimated deposition at Mayport pre- and post-dredging.

NAVFAC Estimated Deposition Volume, cy/yr			
Region	**Predeepening**	**Postdeepening**	**Percent Change**
Turning Basin: Dredged Area	216,600	201,400	-7%
Turning Basin: Nondredged Area	172,900	194,200	12%
Turning Basin: Total	389,500	395,700	2%
Entrance Channel	195,100	208,000	7%
Federal Channel	232,200	236,200	2%

METHODS TO REDUCE SHOALING: The identification of processes that contribute to shoaling in navigable waterways not only allows for the anticipation of future dredging needs but also should provide the basis for reducing sedimentation.

Some methods can be implemented in the design of the harbors and entrances. Harbors have less sedimentation when they are situated on the outside of a river bend versus the inside or a straight stretch of channel. Entrances to riverine harbors should be angled in the downstream direction to reduce the direct import of fines. Channels should be aligned to naturally deep water or, in the extreme case, can be realigned to nearby deeper waters if excessive sedimentation is a problem. This is an expensive endeavor and it should be noted that deep water may not be stationary over longer time scales.

Structures are the most prevalent method of reducing shoaling in existing harbors and channels. Dikes can be installed along navigable rivers as a flow training method to concentrate flow to the center and decrease erosion on high energy river bends (Parchure 2005). Dikes also reduce erosion along the natural banks, preventing this material from moving to the channel center. Coastal inlets often feature jetties to keep the channel clear of the coarse-grained sediment in the littoral zone. A weir-jetty system can be implemented to allow sediment passage over the jetty for capture in a deposition basin adjacent to the jetty on the updrift side of net alongshore sediment transport. Storm-induced waves can carry sediment from a different direction than is typical, so weirs can be installed on the downdrift jetty as well in preparation for these episodic events, as was done at Port Canaveral, FL, after the 2004 hurricane season caused high shoaling rates (CPA 2009). A current deflecting wall (CDW) can be used on harbor entrances to reduce the formation of eddies that occur from the water exchange between the harbor and channel that allows for sediment to enter the harbor (Parchure 2005).

There are nonstructural methods that can be implemented in the upstream environment of the navigation channel or harbor as well as on site to reduce shoaling. On the watershed scale, sedimentation due to river inflow can be inhibited by reducing sediment that reaches the river or its tributaries. Increased land cover in the floodplain will decrease erosion by wind or surface run-off. Additionally, vegetated banks upstream of or surrounding navigable waters will keep natural channel banks intact and less susceptible to erosion. It is particularly important to monitor these areas after prolonged drought when soil erodibility is high. Sediment traps, which lower the energy in a channel reach and act as net deposition regions primarily for bedload or coarser-grained suspended load (i.e., more rapidly settling), can be implemented in rivers to reduce shoaling downstream of the trap. A similar method is used on the Snohomish River at Everett, WA, where a deposition basin located upstream is dredged roughly every other year (USACE 2012).

PATH FORWARD: Processes were discussed specifically in the context of Mayport so they could be illustrated in a real system with a known dredge history. Moving forward, Mayport and additional sites will undergo in-depth analyses to quantify impact of infill processes presented in this report and new processes that perhaps better fit other sites. This knowledge will be used collectively for the development of a generalized tool or method to aid in estimating future dredging requirements and sediment classification and to facilitate the evaluation of placement options based on site-specific data.

CONCLUSIONS: This DOER TN gives an overview of channel and harbor infill processes and how site-specific forcing data including river discharge, wind, waves, and tides impact how and where shoaling occurs. Sediment classification varies throughout the channel due to these processes and generally shifts from fine to coarse grained in the seaward direction. Because the intention is to identify and quantify impacts to future dredging requirements, the effects of new work deepening and widening of channel was also considered in relation to changes in shoaling patterns.

ACKNOWLEDGMENTS: This research was funded by the USACE Dredging Operations and Environmental Research Program. The DOER Program Manager is Dr. Todd S. Bridges, ERDC Environmental Laboratory.

POINTS OF CONTACT: For additional information regarding this technical note, contact the authors Lauren Coe (601-634-2864), Lauren.A.Coe@usace.army.mil, or Ashley Frey (601-634-2006), Ashley.E.Frey@usace.army.mil. Additional information pertaining to the DOER Program may be obtained from Dr. Bridges (601-634-3626), Todd.S.Bridges@usace.army.mil. This technical note should be cited as follows:

> Coe, L., and A. E. Frey. 2016. *Evaluation of channel infill processes in relation to forcing data*. ERDC TN-DOER T12. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

REFERENCES

Brown, G. L. 2013. *A simplified analytic investigation of the riverside effects of sediment diversions*. ERDC/CHL CHETN-VII-13. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Bruun, P. 1994. Engineering projects in coastal lagoons. *Elsevier Oceanography Series* 60:507–533 (520–521).

Canaveral Port Authority (CPA). 2009. *Port Canaveral south jetty deposition basin entrance channel sediment trap*. Canaveral Port Authority, Cape Canaveral, FL.

Chen, S. N., L. P. Sanford, and D. K. Ralston. 2009. Lateral circulation and sediment transport driven by axial winds in an idealized, partially mixed estuary. *Journal of Geophysical Research: Oceans (1978–2012)* 114.

Eisma, D. 1998. *Intertidal deposits: River mouths, tidal flats, and coastal lagoons*. Vol. 16. Boca Raton, FL: CRC Press, 377–381.

Giardino, D. 2009. *Analysis of the physical forcing mechanisms influencing salinity transport for the Lower St. Johns River*. Orlando, FL: University of Central Florida.

Maggi, F. 2005. *Flocculation dynamics of cohesive sediment.* Delft, South Holland: Faculty of Civil Engineering and Geosciences, Delft University of Technology.

Naval Facilities Engineering Command (NAVFAC). 2008. *Final EIS for the proposed homeporting of addition surface ships at Naval Station Mayport, FL*. Final Environmental Impact Statement. Jacksonville, FL: U.S. Naval Facilities Engineering Command.

Ariathurai, R., J. Golden, Jr., W. H. McAnally, Jr., G. A. Stout, and J. Neiheisel. 1983. Shoaling processes in navigable waters. *Journal of Waterway, Port, Coastal and Ocean Engineering* 109:199–221.

National Oceanic and Atmospheric Administration (NOAA). 2014. *Tides and currents: St. Johns River operational forecast system* (SJOFS). (salinity) http://tidesandcurrents.noaa.gov/ofs/ofs_animation.shtml?ofsregion=sj&subdomain=0&model_type=salinity_nowcast_jx (currents) http://tidesandcurrents.noaa.gov/ofs/ofs_animation.shtml?ofsregion=sj&subdomain=0&model_type=currents_nowcast_jx Accessed August 2015.

Parchure, T. M. 2005. *Structural methods to reduce navigation channel shoaling*. ERDC/CHL-TR-05-13. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Rosati, J. D., and N. C. Kraus. 2000. *Shoal-reduction strategies for entrance channels*. ERDC/CHL CETN-IV-22. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Schoellhamer, D. H. 2000. Influence of salinity, bottom topography, and tides on locations of estuarine turbidity maxima in northern San Francisco Bay. *Proceedings in Marine Science* 3:343–357.

Scully, M. E., C. Friedrichs, and J. Brubaker. 2005. Control of estuarine stratification and mixing by wind-induced straining of the estuarine density field. *Estuaries* 28:321–326.

Speer, P. E. 1984. *Tidal distortion in shallow estuaries.* WHOI-84-25. Woodshole, MA: Woodshole Oceanographic Institution.

Thomas, R. C., and L. M. Dunkin. 2012. *U.S. Navy FCA shoaling study: Demonstration project Mayport, FL*. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

U.S. Army Corps of Engineers (USACE). 2012. *Final environmental assessment. FY 2012-2018 routine maintenance dredging and disposal Snohomish river navigation channel, downstream and upstream settling basins, Everett, Washington. April 2012*. Seattle, WA: U.S. Army Corps of Engineers, Seattle District.

United States Geological Survey (USGS). 2015. *National water information system*. St. John's River at Jacksonville Site. http://waterdata.usgs.gov/nwis. Accessed August 2015.

Walton, T. L. Jr. 2002. *Tidal velocity asymmetry at inlets*. ERDC/CHL CHETN IV-47. Vicksburg, MS: U.S. Army Engineer Research and Development Center.